Estimation of bearing capacity of geosynthetic-reinforced foundation soil based on increased angle of internal friction concept

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ABSTRACT: The task of estimating the bearing capacity of geosynthetic-reinforced foundations has been studied extensively over the last few decades. Researchers have investigated the effect of geosynthetic reinforcement on the bearing capacity parameters that are included in the bearing capacity equation as well as on the ultimate bearing capacity of foundation soils. The analyses have considered different failure mechanisms of geosynthetic-reinforced foundation soils, such as wide-slab and deep-footing mechanisms. The former considers an equivalent footing width, and the latter takes an equivalent embedded depth for the geosynthetic-reinforced foundation system. The improvement of bearing capacity of geosynthetic-reinforced foundation soil has also been analysed by considering an improvement in the bearing capacity factors. For unreinforced soils, these factors are a function of the angle of internal friction of soil, ϕ. This paper therefore presents an analysis of the bearing capacity of a geosynthetic-reinforced foundation soil based on the use of improved bearing capacity factors. The bearing capacity ratio of a single-layer geosynthetic-reinforced foundation soil observed in an experimental study (with and without wraparound ends) is used to calculate the equivalent angle of internal friction, ϕ_R, using Terzaghi's equation. The results reveal that by using a single-layer of geosynthetic in sand at the optimum burial depth, the increase in the value of the internal friction angle is about 13% for reinforced foundation soils without wraparound ends, and about 16% for reinforced foundation soils with wraparound ends.

Keywords: Angle of internal friction; Bearing capacity; Geosynthetic reinforcement; Sand; Strip footing; Terzaghi's Equation

1 INTRODUCTION

Using geosynthetic reinforcements to improve the bearing capacity of weak foundation soils has become a common ground improvement technique in the construction industry. Thus, the task of estimating the bearing capacity of geosynthetic-reinforced foundation soils is of utmost significance and has been studied extensively over the last few decades (Binquet and Lee 1975; Schlosser, Jacobsen, and Juran 1984; Huang and Tatsuoka 1988; Espinoza and Bray 1995; Kurian, Beena, and Kumar 1997; Wayne, Han, and Akins 1998). Researchers have investigated the effect of geosynthetic reinforcement on the bearing capacity factors, N_c, N_q and N_γ, associated with cohesion, surcharge and unit weight of the soil, respectively, which are used in Terzaghi's bearing capacity equation, as well as on the ultimate bearing capacity of the reinforced foundation soil (Khing et al. 1993; Omar et al. 1993; Das, Shin, and Omar 1994; Shin and Das 2000; Chen 2007; Chen, Abu-Farsakh, and Sharma 2013; Chakraborty and Kumar 2014). The analyses considered different failure mechanisms of reinforced foundation soils, such as wide-slab and deep-footing mechanisms (Huang and Tatsuoka 1988, 1990; Huang and Menq 1997). The former considers an equivalent footing width, and the latter takes an equivalent embedded depth for the geosynthetic reinforced foundation system. The improvement of bearing capacity of geosynthetic reinforced foundation soil has also been analysed by considering an improvement in the bearing capacity factors. A few studies show that reinforcing the foundation improves the bearing capacity factors (Chakraborty and Kumar 2014). For unreinforced soils, these factors are just a function of angle of internal friction of soil, ϕ. Thus, we can assume that the geosynthetic reinforcement improves the angle of internal friction of the foundation soil. This paper, therefore, presents an analysis of bearing capacity of reinforced foundation soils based on the use of improved bearing capacity factors to propose an equivalent angle of internal friction for reinforced foundation soils, ϕ_R. The methodology is to apply the bearing capacity ratio from the experimental study conducted by Kazi, Shukla, and Habibi (2015a) on Terzaghi's equation and find an equivalent angle of internal friction with respect to the geosynthetic-reinforced foundation soil. The results can be used to estimate the bearing capacity of a strip footing on sand enhanced with a single-layer of geosynthetic reinforcement with or without wraparound ends.

2 EXPERIMENTAL DATA

An extended experimental study on the bearing capacity of a strip footing resting on a sand bed and reinforced by a single geosynthetic reinforcement layer was conducted by the Geotechnical Research Group at Geotechnical Laboratory of Edith Cowan University (Kazi et al. 2015a; Kazi, Shukla, and Habibi 2015b). They also investigated the effect of wraparound ends on the bearing capacity ratio in various embedment depths of footing. Figure 1 shows the geometry of their models. The variable parameters were the footing embedment depth D_f and the relative density of sand D_r.

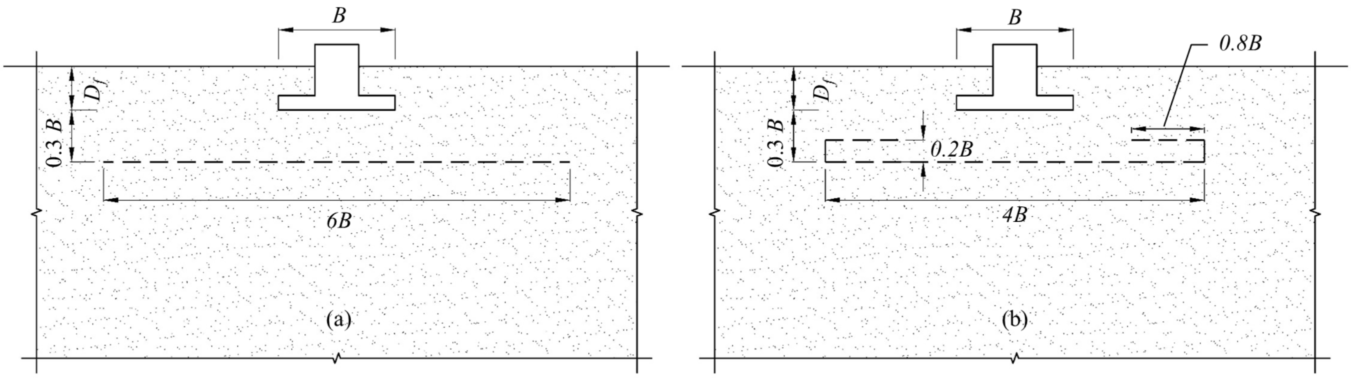


Figure 1. Geometry of model tests: (a) without wraparound ends; and (b) with wraparound ends

Their results showed that the bearing capacity ratio (*BCR* as shown in Eq. (1)) was higher in lower relative densities with its maximum of 2.75 at D_r =50% (for the models with wraparound ends) and minimum of 1.63 at D_r =90% (for the models without wraparound ends).

$$BCR = \frac{q_{u-R}}{q_{u-U}} \tag{1}$$

where q_{u-R} and q_{u-U} are the ultimate bearing capacity of reinforced and unreinforced models, respectively. In the present study, the experimental values observed by Kazi et al. (2015a) for the bearing capacity ratio are used to investigate the effect of a single layer of geosynthetic reinforcement on the internal friction angle of sand.

3 METHODOLOGY

The present study follows the procedure as explained below for calculating an equivalent angle of internal friction with respect to the reinforced foundation (ϕ_R).

3.1. *Extracting BCR from experimental data*

As mentioned before, the *BCR* values are first extracted from the experimental study of Kazi et al. (2015a) for a single-layer of geosynthetic reinforcement in two cases: with and without wraparound ends, as shown in Table 1.

Table 1: *BCR* values used from experimental work (Kazi et al. 2015a)

D_r / D_f/B	50%		70%		90%	
	Without wraparound ends	With wraparound ends	Without wraparound ends	With wraparound ends	Without wraparound ends	With wraparound ends
0	2.00	2.75	1.99	2.24	1.80	2.10
0.25	1.80	2.40	1.93	2.16	1.73	2.00
0.5	1.67	2.17	1.80	2.00	1.67	1.97
0.75	1.57	2.00	1.76	1.94	1.69	1.97
1	1.55	1.97	1.69	1.91	1.71	1.93
1.25	1.58	2.00	1.66	1.85	1.67	1.87
1.5	1.55	2.00	1.67	1.84	1.63	1.80

3.2. *Calculating theoretical bearing capacity for unreinforced cases*

For all embedment depths, unreinforced failure pressure is calculated using Terzaghi's equation (Eq. (2)).

$$q_{u-U} = D_f \times \gamma \times N_q + cN_c + \frac{1}{2}\gamma \times B \times N_\gamma \tag{2}$$

where N_q, N_c, and N_γ are the bearing capacity factors in regards to surcharge, cohesion and dry unit weight of foundation, respectively, as defined below (Bowles 1996; Shukla 2014; Shukla 2015):

$$N_q = e^{\pi \tan\phi} \times \tan^2(45^\circ + \frac{\phi}{2}) \tag{3}$$

$$N_c = (N_q - 1) \times \cot\phi \tag{4}$$

$$N_\gamma = 2(N_q + 1) \times \tan\phi \tag{5}$$

3.3. *Calculating qu-R by applying BCR values on qu-U*

The reinforced bearing pressure is then calculated by multiplying the unreinforced values from Eq. (2) at *BCR* values in Table 1.

$$q_{u-R} = q_{u-U} \times BCR \tag{6}$$

3.4. *Calculating the equivalent improved friction angle ϕR*

The equivalent angle of internal friction, ϕ_R with respect to the geosynthetic reinforced foundation soil is then calculated by back calculation of Terzaghi's equation.

$$q_{u-R} = D_f \times \gamma \times N_{q-R} + cN_{c-R} + \frac{1}{2}\gamma \times B \times N_{\gamma-R} \rightarrow \text{Find } \phi_R \tag{7}$$

where $N_{q\text{-}R}$, $N_{c\text{-}R}$, and $N_{\gamma\text{-}R}$ are the bearing capacity factors in respect of the improved angle of internal friction following Eqs. (3) - (5).

4 RESULTS AND DISCUSSSION

4.1. *Equivalent reinforced friction angle ϕ_R*

Figure 2 shows the variation of the average of ϕ_R with ϕ at various relative densities for models with and without wraparound ends. A nearly linear relationship exists between the equivalent reinforced angle of internal friction and the unreinforced one.

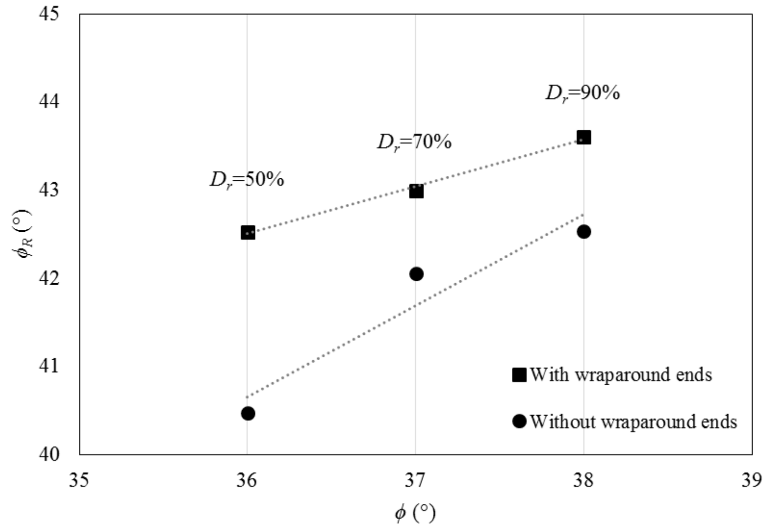


Figure 2. The variation of ϕ_R with ϕ

In order to analyse the effect of geosynthetic reinforcement on the angle of internal friction, two relative parameters are also defined: the friction angle ratio (*FAR* as given in Eq. (8)), and the friction angle improvement factor (I_f as given in Eq. (9)).

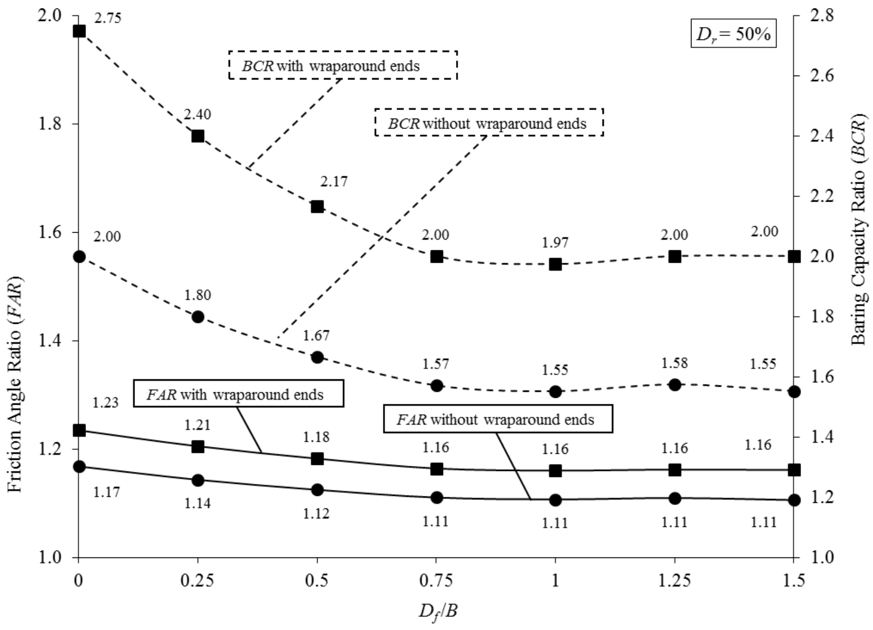
$$FAR = \frac{\phi_R}{\phi_{UR}} \tag{8}$$

$$I_f = \frac{\phi_R - \phi_{UR-U0}}{\phi_{UR-U0}} \times 100 \tag{9}$$

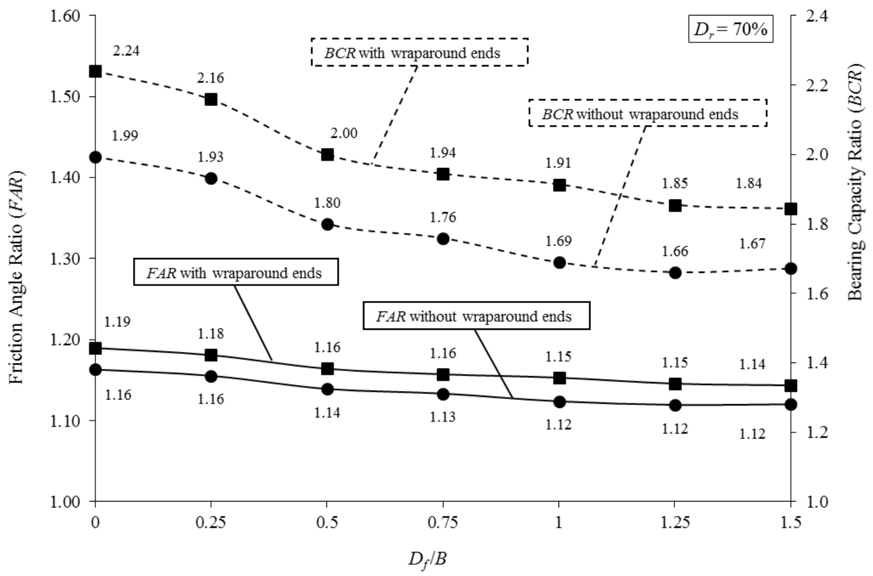
where ϕ_R, ϕ_{UR} and $\phi_{UR\text{-}U0}$ are the equivalent friction angle (regarding D_f and/or reinforcement), the unreinforced friction angle at D_f, and the unreinforced friction angle at $D_f = 0$, respectively. Following is a brief discussion on the analysis of *FAR* and I_f.

4.2. *Analysis of FAR*

Figures 3(a)-3(c) compare the variation of *FAR* and *BCR* with the embedment depth D_f for reinforced foundations (with and without wraparound ends) at relative densities of 50%, 70% and 90%. It can be seen that by increasing the embedment depth, both *FAR* and *BCR* values are reduced. However, *FAR* does not change significantly. For example, for the models with wraparound ends at D_r = 70%, *FAR* decreases from 1.19 to 1.14 with a standard deviation (SD) of 0.02, compared with *BCR* which falls from 2.24 to 1.84 with SD = 0.14. Similarly, for the reinforced models without wraparound ends at D_r = 70%, *FAR* decreases from 1.16 to 1.12 with SD = 0.02, whereas *BCR* reduces from 1.99 to 1.67 with SD = 0.12.



(a)



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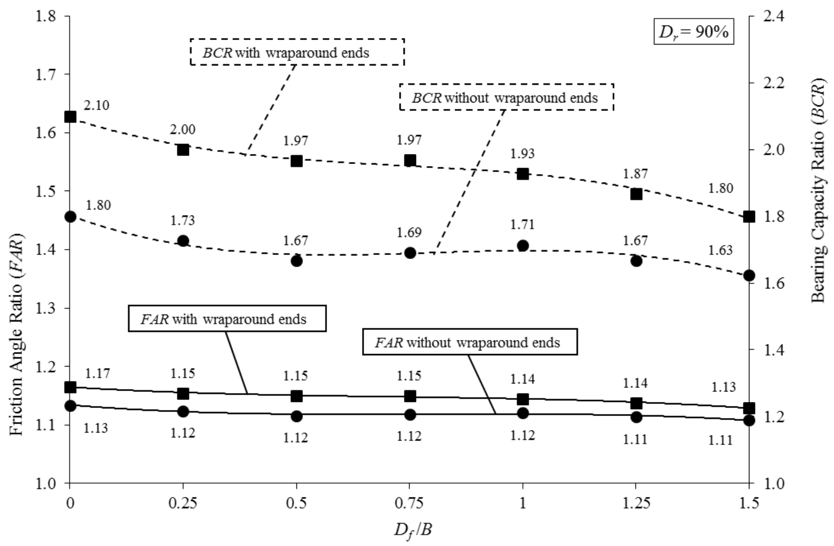


(c)

Figure 3. *FAR* and *BCR* variation with D_f/B for (a) *Dr* = 50%, (b) D_r = 70%, and (c) D_r = 90%

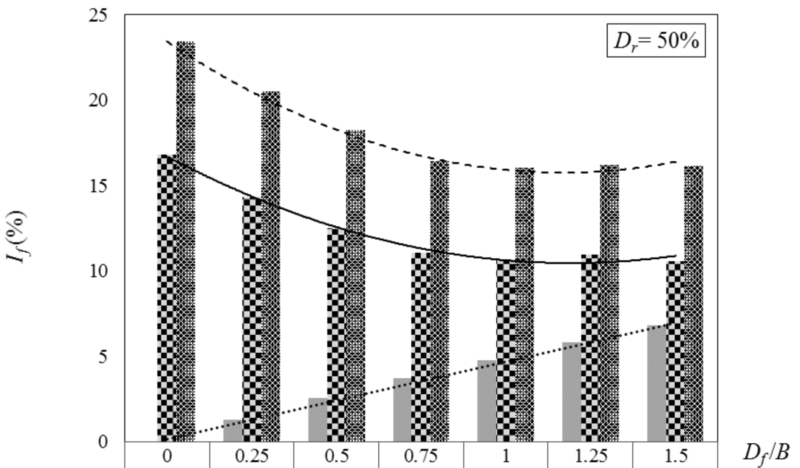
Table 2 compares the values of the mean and standard deviations for *BCR* and *FAR* parameters at each test series. The observation of results reveals that the average value of *FAR* for the models without wraparound ends (1.13) can be used to estimate the equivalent internal friction angle of sand for reinforced foundation soils in a similar arrangement with a standard deviation of 0.02. Similarly, for the models with wraparound ends, *FAR* of 1.16 with a standard deviation of 0.02 can be used to estimate the bearing capacity of foundation soils.

Table 2. Mean and standard deviation of *BCR* and *FAR*

Test Series	Without Wraparound Ends						With Wraparound Ends					
Parameter	*BCR*			*FAR*			*BCR*			*FAR*		
D_r (%)	50	70	90	50	70	90	50	70	90	50	70	90
Mean Value	1.67	1.79	1.70	1.12	1.14	1.12	2.18	1.99	1.95	1.18	1.16	1.15
SD	0.16	0.12	0.05	0.02	0.02	0.01	0.27	0.14	0.09	0.03	0.02	0.01
Total Average	1.72			1.13			2.04			1.16		
SD	0.13			0.02			0.21			0.02		

4.3. *Analysis of I_f*

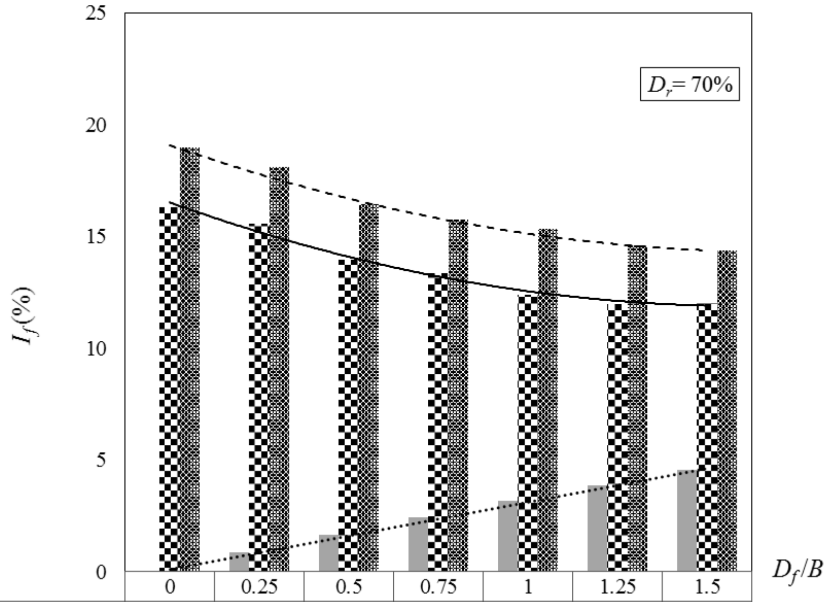
Figures 4(a)-4(c) show the variation of the internal friction angle improvement factor (I_f as calculated from Eq. (9)) with D_f/B for unreinforced and reinforced models. It is notable that equivalent friction angles for unreinforced embedded footings (D_f>0) are also calculated demonstrating the effect of embedment depth on the angle of internal friction of sand. Thus, for the unreinforced shallow footing (D_f= 0), the value of I_f is zero. A comparison of unreinforced and reinforced curves shows that by increasing the embedment depth D_f , the effect of the surcharge load ($D_f \times \gamma$) on the angle of internal friction of sand increases; however, the effect of reinforcement decreases. As an instance, for D_r=50%, the variation of I_f with D_f/B is upward for unreinforced foundation soils, increasing from 0 at D_f/B = 0 to 6.8% at D_f/B = 1.5. On the other hand, curves of I_f for reinforced foundation soils with D_r = 50% is downward, decreasing from 16.8% to 10.6% for models without wraparound ends and from 23.5% to 16.1% for models with wraparound ends when D_f/B increases from 0 to 1.5.



	0	0.25	0.5	0.75	1	1.25	1.5
Unreinforced	0.0	1.3	2.5	3.7	4.8	5.8	6.8
Reinforced without wraparound ends	16.8	14.3	12.5	11.0	10.7	11.0	10.6
Reinforced with wraparound ends	23.5	20.5	18.2	16.4	16.0	16.2	16.1

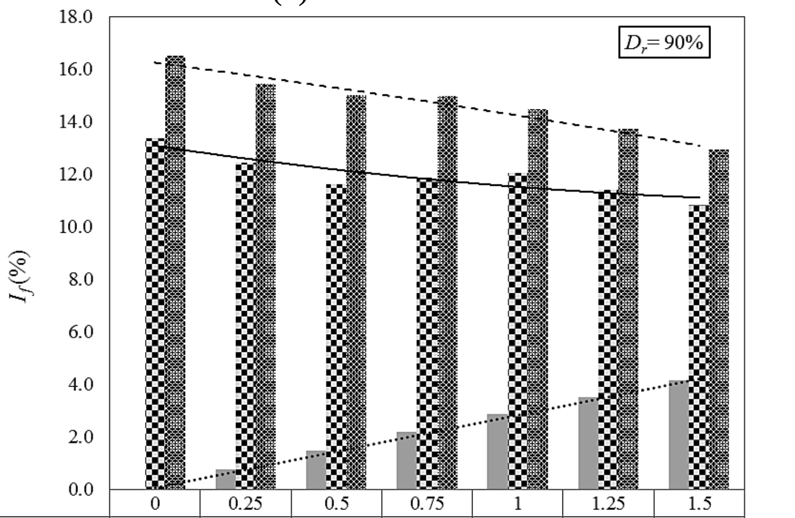
(a)

Figure 4. The variation of I_f with D_f/B for (a) D_r = 50%, (b) D_r = 70%, and (c) D_r = 90%



D_f/B	0	0.25	0.5	0.75	1	1.25	1.5
Unreinforced	0.00	0.84	1.64	2.41	3.16	3.87	4.56
Reinforced without wraparound ends	16.32	15.55	13.93	13.35	12.39	11.96	12.04
Reinforced with wraparound ends	18.98	18.09	16.42	15.73	15.31	14.58	14.37

(b)



D_f/B	0	0.25	0.5	0.75	1	1.25	1.5
Unreinforced	0.0	0.8	1.5	2.2	2.9	3.5	4.2
Reinforced without wraparound ends	13.4	12.4	11.6	11.9	12.1	11.4	10.8
Reinforced with wraparound ends	16.5	15.5	15.0	15.0	14.5	13.7	12.9

(c)

Figure 4. Continued

Kazi et al. (2015a) determined a similar factor for the ultimate bearing capacity of unreinforced and reinforced models (with and without wraparound ends). Their results show that by increasing the embedment depth, the bearing capacity improvement factor increases with a similar trend in both unreinforced and reinforced curves. A comparative study of these two different trends for the present study and the values given by Kazi et al. (2015a) shows that by increasing the embedment depth of footing, the effect of geosynthetic reinforcement on the angle of internal friction of sand decreases; however, the effect of surcharge increases. This can justify the upward trend of the curves representing the variation of the bearing capacity improvement factor with the embedment depth reported by Kazi et al. (2015a).

5 CONCLUSIONS

This paper investigates the effect of a single-layer geosynthetic reinforcement on the angle of internal friction of a sandy foundation under a strip footing. The improved angle of internal friction is determined by back calculation using Terzaghi's equation. Based on the results and discussion, the following conclusions can be made:

- The average friction angle ratio *FAR* for a strip foundation reinforced with a single layer of geosynthetic without wraparound ends is 1.12 for D_r = 50% with SD = 0.02; 1.13 for D_r = 70% with SD = 0.02; and 1.12 for D_r = 90% with SD = 0.01.
- The average friction angle ratio *FAR* for a strip foundation reinforced with a single layer of geosynthetic with wraparound ends is 1.18 for D_r = 50% with SD = 0.03; 1.16 for D_r = 70% with SD = 0.02; and 1.15 for D_r = 90% with SD = 0.01.
- For reinforced strip foundations with a single layer of geosynthetic, an equivalent angle of internal friction (ϕ_R) can be considered as 1.13ϕ and 1.16ϕ for reinforcements without and with wraparound ends, respectively, with SD = 0.02.
- The improvement factor of the angle of internal friction, I_f , for unreinforced and reinforced foundations shows that by increasing the embedment depth of a footing, the effect of surcharge increases, but the effect of reinforcement faces a downward trend.

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